

# MODIS On-orbit Calibration and Characterization

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**Abstract.** MODIS Protoflight Model, launched on-board the NASA EOS Terra spacecraft on December 18, 1999, has been in operation for more than two years, providing the science community calibrated data sets for the global studies of the land, oceans, and atmosphere. MODIS has 36 spectral bands, covering the spectral range from 412 to 14200 nm, and provides spatial resolutions of 0.25 km (2 bands), 0.5 km (5 bands), and 1 km (29 bands) at nadir. The key On-board Calibrators (OBCs) include a Solar Diffuser (SD) and a Solar Diffuser Stability Monitor (SDSM) system for the reflective solar bands calibration, and a V-grooved flat panel Blackbody (BB) for the thermal emissive bands calibration. In this paper, we describe the use of OBCs for the sensor's radiometric calibration and characterization and discuss on-orbit performance. In addition, we provide an assessment on the SD and MODIS optics on-orbit degradation.

## 1. Introduction

The MODERate Resolution Imaging Spectroradiometer (MODIS) Protoflight Model (PFM) is the key instrument on the NASA Earth Observing System (EOS) Terra spacecraft. The instrument was designed to provide the science community improved observations relative to heritage sensors for the long-term global studies of the land, oceans, and atmosphere. Terra was launched on December 18, 1999 in a near sun-synchronous polar orbit (orbit altitude = 705 km) descending southward with a 10:30 am local equator crossing time. Using a two-sided scan mirror, the MODIS 1 km bands sample the earth scenes 1354 times every 1.478 seconds. The  $\pm 55^\circ$  degree scan (relative to nadir) produces a swath of 10 km (at nadir) along track and 2330 km crosstrack. For the 0.5 km and 0.25 km resolution bands, there are 2 sub-samples and 4 sub-samples respectively, corresponding to each 1 km resolution sample. For over two years, Terra MODIS has been performing well on-orbit.

This paper provides a brief overview of the instrument and describes the MODIS on-orbit calibration and characterization through the use of its On-board Calibrators (OBCs). It focuses on the applications of the Solar Diffuser (SD) and Solar Diffuser Stability Monitor (SDSM) system for the sensor's reflective solar bands radiometric calibration and the Blackbody (BB) for its thermal emissive bands radiometric calibration. Results of the system response trending/change and detector noise characterization, derived from on-orbit observations, are presented.

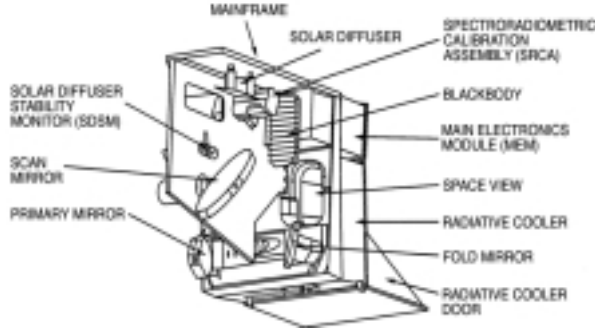
## 2. Instrument Background

MODIS has 36 spectral bands with wavelengths ranging from 412 to 14200 nm. It provides spatial resolutions of 0.25 km (2 bands with 40 along track detectors each), 0.5 km (5 bands with 20 along track detectors each), and 1 km (29 bands with 10 along track detectors each) at nadir. The 36 spectral bands are distributed on four focal plane assemblies (FPAs): VIS, NIR, SW/MWIR, and LWIR. Two of the 1 km resolution bands (bands 13 and 14 at 667 nm and 678 nm), using two rows of detectors in time delay and integration (TDI), provide measurements of the same scene at both low gain and high gain.

MODIS OBCs include an SD/SDSM system for the reflective solar bands (RSB) radiometric calibration, a BB for the thermal emissive bands (TEB) radiometric calibration, and a Spectroradiometric Calibration Assembly (SRCA) for the sensor's spatial and spectral calibration. Figure 1 shows the instrument scan cavity and the on-board calibrators. The sensor views the cold space through the space view port to observe the system level dark response and thermal background.

Pre-launch, the instrument completed various sub-system and system level tests. Key radiometric calibrations in the thermal vacuum included the TEB calibration using an external high emissivity Blackbody Calibration Source (BCS) operated from 170-340K and the RSB calibration using a Spectral Integration Sphere (SIS) operated with a series of lamp levels to provide the necessary dynamic range. In addition, the sensor's response and noise characterization were studied at different instrument temperatures and, for the TEB, at different cold FPA

temperatures. A detailed description of the MODIS instrument characterization and pre-launch calibration results has been provided by Barnes et al. [1].



**Figure 1.** MODIS Scan Cavity and On-board Calibrators

### 3. On-orbit Calibration and Characterization

The MODIS Level 1B algorithm converts instrument digital numbers into geolocated and radiometrically calibrated products. This data is then used for developing a broad range of science products. MODIS L1B primary products are reflectance factors for the RSB and top of the atmosphere (TOA) radiances for the TEB. The RSB (bands 1-19, 26) on-orbit calibration is implemented in the L1B through the use of a series of look-up tables (LUTs) filled with calibration coefficients derived from frequently scheduled SD calibrations (weekly during first two years and biweekly thereafter). The TEB (bands 20-25, 27-36) on-orbit calibration is performed in the L1B using the scan-by-scan OBC BB observations.

#### 3.1 Solar Diffuser and RSB Calibration

The Solar Diffuser was made of Spectralon materials. Its Bi-directional Reflectance Factor (BRF) from 400 to 1700 nm was characterized pre-launch using a scattering goniometer and a known BRF standard reference sample traceable to NIST. On-orbit, the solar diffuser frequently views the Sun and provides updates for the RSB calibration parameters. For a given band, detector, sub-frame (for sub-km bands), and mirror side, the Earth view reflectance factor,  $\rho_{EV} \cdot \cos(\theta_{EV})$ , can be expressed as [2]

$$\rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot dn_{EV} \cdot d_{ES(EV)}^2, \quad (1)$$

where  $m_1$  is a reflectance scaling factor,  $dn_{EV}$  is the Earth view corrected digital number (corrected for instrument background, temperature variation, and scan angle response), and  $d_{ES(EV)}$  is the Earth-Sun distance at the time of the Earth view observation. Similarly, the scaling factor is computed from SD observations using SD BRF with its on-orbit degradation ( $\Delta_{SD}$ ) corrected,

$$m_1 = \frac{BRF \cdot \cos(\theta_{SD})}{dn_{SD} \cdot d_{ES(SD)}^2} \cdot \Delta_{SD} \cdot \Gamma, \quad (2)$$

where  $\Gamma$  is the vignetting function for bands that use the SD attenuation screen during calibration,  $d_{ES(SD)}$  is the Earth-Sun distance during the SD calibration, and  $dn_{SD}$  is solar diffuser corrected digital number.

The distance correction is needed in both (1) and (2) since the SD calibration and the Earth views are not performed at the same time. For the bands that do not use the SD screen,  $\Gamma$  is set to 1. The SD on-orbit degradation ( $\Delta_{SD}$ ) is determined from the Solar Diffuser Stability Monitor. The SDSM consists of a solar integrating sphere with 9 filtered detectors monitoring wavelengths ranging from 410 to 940 nm. It works as a ratioing radiometer, viewing the Sun through an attenuation screen and the light diffusely reflected from the SD alternately during calibration and thus tracks the SD on-orbit degradation [3].

#### 3.2 Blackbody and TEB Calibration

MODIS TEB on-orbit calibration is performed using a full aperture V-grooved flat panel Blackbody (BB) with 12 thermal sensors embedded in the BB substrate. The pre-launch characterization of OBC BB was achieved using an external high emissivity Blackbody Calibration Source (BCS), referenced to NIST temperature standards. On-orbit, the OBC BB is capable of operating in a temperature range from 270 to 315 K. TEBs use a quadratic algorithm in the calibration. BB warm-up and cool-down data are used to derive the detectors' offset ( $a_0$ ) and non-linear ( $a_2$ ) terms on-orbit. The first order coefficient ( $b_1$ ) is determined scan-by-scan from OBC BB observations, except for B21 (a low gain band for fire detection) that uses fixed gain coefficients due to the limited dynamic range from the OBC BB temperature. The TOA Earth scene radiance,  $L_{EV}$ , is given [2] by

$$L_{EV} = \frac{1}{RVS_{EV}} \left\{ a_0 + b_1 \cdot dn_{EV} + a_2 \cdot dn_{EV}^2 - (RVS_{SV} - RVS_{EV}) \cdot L_{SM} \right\}. \quad (3)$$

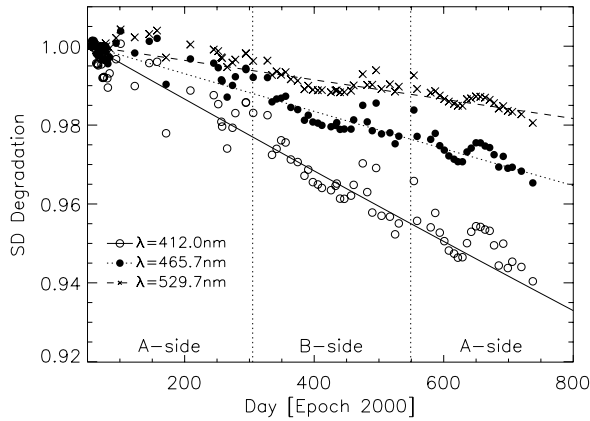
In the TEB calibration algorithm, the thermal emission from the scan mirror ( $L_{SM}$ ) must be considered. Because the sensor views the deep space and the Earth scene at different angles of incidence (AOI) and the scan-mirror emission varies with AOI, the scan mirror term cannot be removed completely by subtracting the earth view (EV) and space view (SV) values. The  $RVS_{EV}$  and  $RVS_{SV}$  in (3) are the responses versus scan angle at the Earth view and space view respectively. When applying the same calibration algorithm to the OBC BB to compute the linear term ( $b_1$ ), the scan cavity's thermal contribution has to be considered. Thus,

$$b_1 = \frac{1}{dn_{BB}} \left\{ RVS_{BB} \cdot \epsilon_{BB} \cdot L_{BB} + (RVS_{SV} - RVS_{BB}) \cdot L_{SM} + RVS_{BB} \cdot (1 - \epsilon_{BB}) \cdot \epsilon_{CAV} \cdot L_{CAV} - (a_0 + a_2 \cdot dn_{BB}^2) \right\}. \quad (4)$$

The OBC BB with emissivity of  $\epsilon_{BB}$  is set at 290K for normal on-orbit operation. The scan mirror and cavity (emissivity of  $\epsilon_{CAV}$ ) temperatures used for computing the corresponding radiance terms are provided from on-orbit telemetry.

#### 4. Results and Discussions

Figure 2 shows the SD degradation at three different SDSM detectors wavelengths, corresponding to MODIS B8 (412 nm), B3 (469 nm), and B11 (531 nm). The degradation for other longer wavelength RSB is much smaller. Due to a design defect in the existing SDSM, the signals from the Sun view through the attenuation screen have shown large ripples (as high as 15%) that cause large uncertainties in the original approach [3] of computing SD degradation.

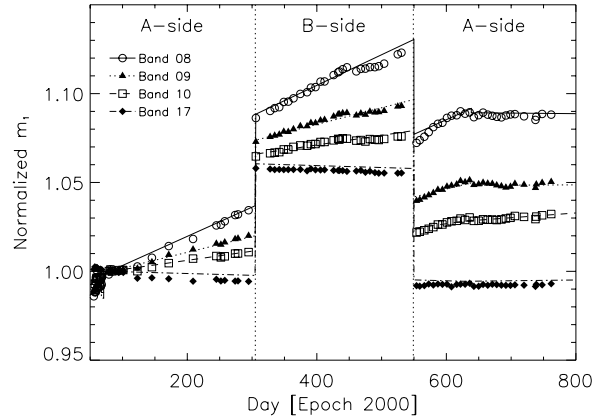


**Figure 2.** MODIS Solar Diffuser On-orbit Degradation

Because of this, an alternative approach [3] has been developed to enable precise tracking of the SD degradation. The new approach uses the signal from one of the SDSM detectors (the longest wavelength one with minimal SD degradation) to remove the ripples from the other SDSM detectors. Although small ripple effects still exist in Figure 2, the overall trend of wavelength dependent degradation is obvious. The SD degradation shown in Figure 2 is removed from RSB calibration but the degradation trending uncertainty up to 0.3% (worst case at 412nm, 1 sigma) has to be added to final RSB calibration uncertainty (about 2% for the reflectance factor). Initial Terra MODIS operational activities included a series of spacecraft yaw maneuvers that allowed the on-orbit study of the SD relative BRF. The on-orbit relative results from the yaw maneuvers agreed with the pre-launch values to within  $-0.25\%$ . The yaw data collected with and without the SD attenuation screen have been used to evaluate the screen vignetting function.

The above SD degradation is computed with respect to the first exposure on-orbit. It does not include any potential degradation from SD ground calibration to the first exposure on-orbit. However, using response coefficients derived from ground SIS

calibration and that from on-orbit SD calibration, we did not find any SD degradation (wavelength dependent) during this period. In addition to the SD degradation, MODIS has shown mirror-side dependent degradation, especially for the visible bands. To first order, the sensor's degradation is corrected by the time dependent and mirror side dependent coefficients at a fixed angle of incidence (AOI). To further improve data quality, a time dependent response versus scan angle (RVS) approach has been added to the L1B algorithm. Shown in Figure 3 are the reflectance scaling factor (2) trending results for several RSB bands (B8 at 412 nm, B9 at 443 nm, B10 at 488 nm, and B17 at 905 nm) over two years using the mirror side 1. There are three epochs for Terra MODIS on-orbit operation: the initial A-side electronics configuration, B-side electronics configuration, and the current A-side electronics configuration. The response changes from one configuration to another were expected. The response degradation in Figure 3 is wavelength dependent. For MODIS, the shortest wavelength band (B8) has shown about 10% degradation. In the NIR (e.g. 905 nm) range, the response degradation is very small. Mirror side 2 has similar trend but with a slightly higher degradation rate. It should be pointed out that the degradation will certainly change the polarization characteristics. Since November 2001, the degradation has essentially stopped. The cause of this is still unknown.

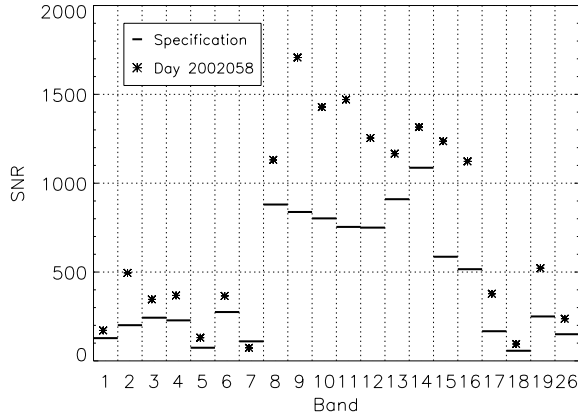


**Figure 3.** Reflectance Scaling Factor for B8 (412 nm), B9 (443 nm), B10 (488 nm), and B17 (905 nm)

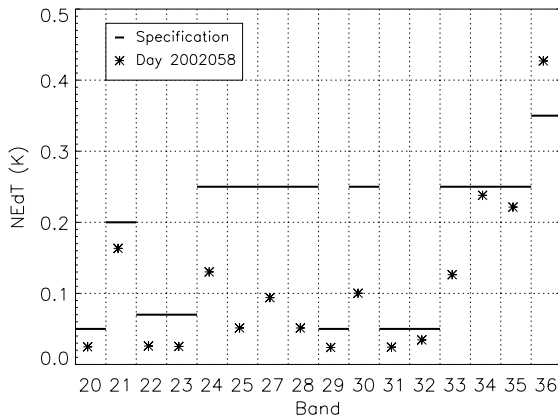
The on-orbit detector's signal-to-noise ratio (SNR) is constantly monitored using data from SD and space views. The SNR at typical radiance levels is interpolated from the values at the measured levels. On-orbit RSB SNR results are shown and compared with the specifications in Figure 4 for the middle detector of each band. Except for several noisy and out-of-family detectors (see the one in B7), all RSB bands meet their specification on-orbit.

For the TEB, the noise characterization is evaluated by the noise-equivalent-temperature-difference (NEdT). This is derived from OBC BB data collected at various temperature settings. The results at typical radiance are compared with the

specification. The smaller the NEdT the better the detector performs. On-orbit observations (see Figure 5) have shown that most of the TEB detectors have been performing within their specification except for B36 which was identified pre-launch of having noise above its specification.

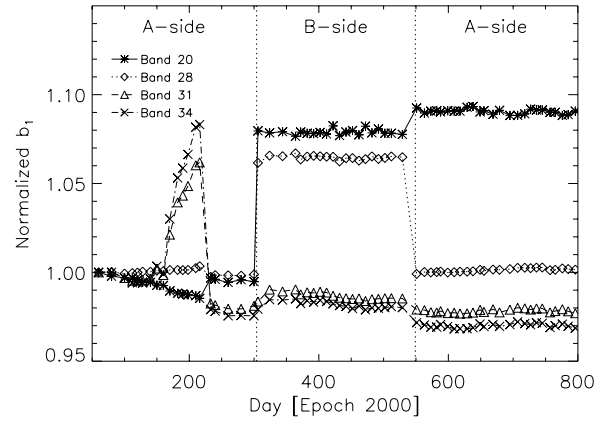


**Figure 4.** MODIS Reflective Solar Bands On-orbit Signal-to-Noise Ratio (middle detector only)



**Figure 5.** MODIS Thermal Emissive Bands On-orbit Noise-Equivalent-Temperature-difference (middle detector only)

In Figure 6, the response of 4 thermal emissive bands is trended. B20 is on the MWIR FPA and B28 B31 and B34 are on the LWIR FPA. MODIS Bands 31-36 use photoconductive detectors that are usually sensitive to the FPA temperature. When MODIS operated in the initial A-side configuration, there was a period of time (around day 200) that the cold FPA got warmer due to the loss of the cooler capacity (margin). This is reflected in the large response change of B31 and B34. Since the TEBs are calibrated on-orbit scan-by-scan, the L1B calibration algorithm still works for retrieving the Earth radiance in spite of the response variations. Again, the response change from A-side to B-side electronics is expected. For B20, there is also a difference between the two A-side configurations due to different FPA biases. Except for configuration differences, the MODIS TEB responses have been quite stable during its more than two years of on-orbit operation.



**Figure 6.** Thermal Emissive Bands Response (middle detector only) for B20 (3750 nm), B28 (7325 nm), B31 (11030 nm), and B34 (13635 nm)

## 5. Summary

MODIS on-board calibrators have been used for the sensor's on-orbit calibration and characterization. The SD degradation and other optics degradation effects, including the AOI dependent response, are included in the calibration algorithms. For over two years, Terra MODIS has been performing well and is continuing to provide calibrated data sets for a broad user community. MODIS Level 1B products and other science products are made freely available to the public through NASA Goddard Earth Science (GES) Distributed Active Archive Center (DAAC: <http://daac.gsfc.nasa.gov/>).

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## Reference

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